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# **BUILDING SOUND MOBILITY MODELS FOR AD HOC NETWORK SIMULATION**

**University of Michigan**

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# 1 SUMMARY

This technical report describes work performed on building sound mobility models for the simulation studies of mobile ad hoc networks. Specifically, this project aimed at developing tools and modules to better facilitate the study of mobile ad hoc networks, which tends to be heavily simulation based. The main motivation for this study was the fact that the use of mobility models can become a source of error in simulation studies of ad hoc networks. For example, the widely used random waypoint model found in our previous work had a speed decay problem. The network-wide average node speed consistently dropped as simulation time increased using the default parameter setting of the model. The study found that this was not a problem exclusive to the random waypoint model, but common to all models which select travel time and travel distance independently. The research findings also pointed directly to how stationary speed decay-free models were constructed. The problems addressed in this project build on prior work but also expand to a broader area within ad hoc networking research. Specifically, this project addressed the central problem on how to make ad hoc network simulation studies more scientific and more quantitatively reliable. This project addressed three aspects: (1) developing mobility models that are stationary and mathematically tractable, (2) developing mobility models that more closely represent real movement, and (3) developing a simulation module of IEEE 802.15.4 for the NS2 simulator. This project addressed the area of stochastic modeling, renewal theory and computer simulation. In particular, it involved building better mobility models that capture the characteristics of movement pattern in different scenarios. The project also built simulation modules that enabled various applications to utilize the constructed mobility models.

# 2 INTRODUCTION AND MOTIVATION

The movement of their constituents typically characterizes mobile systems. The nature and pattern of movement, e.g., speed, direction, and rate of change, has a dramatic effect on protocols designed to support mobility modeling. The patterns and nature of movement often dictate the design of such protocols and systems. The mobile computing community has turned to *simulating* the movement of nodes and users. It is difficult to recreate movement found in the physical world. Analytical approaches to movement have limited applicability and often only produce estimates and bounds under specific assumptions. Mobility models used to generate simulated movement typically consists of a set of rules and stochastic processes triggered by these rules. The derivation of mobility models is often heuristic-based, attempting to reproduce the real movement of the particular system under consideration. For example, the [Hong99] group mobility model reflected the movement of platoons. The model contains specifications for the group movement and the movement of soldiers/nodes within each group. The pursuing model [Hu00] described the scenario where groups of nodes track moving targets. [Camp02] provides details of a survey of existing mobility models.

However, without careful examination, heuristic based methods can lead to hidden problems in a mobility model. The most commonly used mobility model in the ad hoc networking research community is the *random waypoint model*, e.g., see [Broch98]. This model produces “random” and independent movement of nodes where nodes alternate between moving and pausing modes. In [Yoon03Infocom] the study showed that this model had a speed decay problem. Research found that the average node speed decays from the start of the simulation over time to a steady state. The intuitive explanation behind this is that over time more and more nodes tend to get “stuck” in a slow trip caused by a very low speed and a relatively long distance. This phenomenon was within the context of Palm theory [Palm]. In the extreme case when speeds are chosen from a uniform distribution ranging from zero to some maximum speed, the steady state is zero. Under this particular parameter setting, the default in the NS2 simulator [NS2] and used by most ad hoc network studies, the average nodal speed continuously decreases to zero.

This means that the level of mobility in the network never stabilizes. Consequently, with this parameter setting, the researcher cannot measure results as time averages or qualitative or quantitative conclusion obtained. Even in the non-degenerative case where the minimum speed is non-zero and there exists a positive steady state average nodal speed, the initial speed decay is still present.

Research recently found that the speed decay problem identified with the random waypoint model is present in a large family of mobility models. More specifically, any model that involves choosing node speed and travel distance *independently* suffers from speed decay. This applies to both entity mobility models where nodes move independently of each other and group mobility models where nodes within a group move in a coordinated fashion. The intuitive explanation for this phenomenon is similar to that mentioned before. This problem is explained more succinctly using the basic renewal theory and the equilibrium renewal processes. [Yoon03Mobicom] provided a detailed analysis and a constructive method with which one can obtain a stationary mobility process out of any mobility model of this family. This process is obtained by starting in the steady state at the beginning of the simulation. There are limitations to the method presented in [Yoon03Mobicom]. In particular, it is not clear how similar methods are developed when nodes' movements are correlated. There is also the equally important issue of what constitutes a realistic mobility model. There is a great need for a method to develop mobility models that represent real movement for simulation studies.

Motivated by the above, this project had two focuses. The first was the formal study of constructing stationary processes out of individual marked renewal processes. This study improved on the work reported in [Yoon03Mobicom], and applies to larger class of mobility models including group mobility models. The results from this study are reported in [Yoon05TMC]. The second focus was on deriving mobility models using real movement data traces. To that end, researchers at Dartmouth College collected data traces on their campus of wireless LAN users. Using collected data traces a Markov model was constructed to capture the stochastic properties of user movement. This model predicted user movement and generated data traces, which are stochastically similar to real traces, for simulation purposes. Findings and results from this study are in a report that will be submitted for publication soon.

The above two focuses can be viewed as the *analysis* and *synthesis* aspects of this project, respectively. In addition, a ZigBee [ZigBee] simulation module was built for NS2, for the purpose of testing and evaluating mobility models and providing mobile applications scenarios for such studies. The overall goal of this research is to understand how mobility models can function as a simulation tool to view a complex combination of random processes; and to build mobility models that are accurate and realistic for simulation studies. The subsequent sections documented this network modeling and simulation project. The project goals were achieved over the course of the project's performance period (from April 2004 to January 2005). Further research is recommended on the use of mobility models and prediction methods to improve service provisioning and Quality of Service (QoS) of mobile systems.

## 3 METHODS, ASSUMPTIONS, AND PROCEDURES

### 3.1 Objectives and Methodologies

As outlined in the previous section, this project has an analysis aspect and a synthesis aspect in the study of mobility models. In addition, simulation modules for the IEEE 802.15.4 standard were developed. Consequently, this project consists of three components. Below describes the objectives and basic methodologies for each of these components.

- The objective of building stationary mobility models is to produce models that can produce simulation results that are reliable both qualitatively and quantitatively. As mentioned in the previous section, mobility researcher need to carefully examine the models and the method with which the models are used in a simulation study to avoid interjecting sources of error. The basic methodology adopted in this study is to treat a given mobility model as an ensemble of random processes prescribed by a number of basic random elements, e.g., nodal speed, direction, and so on. The mobility models constructed were characterized by these basic random elements. The basic methodologies employed in this study included the following steps: Mobility models were classified according to the independence between constituents of the system, and then further classified based on the random elements driving the movements. The transient and stationary behavior of these models was studied to determine how they should be used in a simulation study. Base on this result, a constructive method was derived to build a composite mobility model for the mobility model being studied, that is stationary and more suitable for simulation studies
- Constructing mobility models from real movement data naturally results in more realistic representation of movement than models constructed using elementary random components (e.g., the ones studied earlier). Real movement data also helps in evaluating the performance of protocols and algorithms designed for these systems. A primary reason why simulation is so often used is its flexibility and low cost compared to actual experiments. Network systems are designed with the goal of being implemented and used in the real world. Therefore, it's highly desirable to make simulation systems as realistic as possible within the constraints of complexity and cost. One approach is to use trace-driven simulation, which use real traces to trigger events in a simulation. Such an approach usually requires large amount of measured data. A cheaper but equally efficient way of achieving this is to build synthetic models after real data traces so that they generate synthetic/simulated traces similar (stochastically) to a real trace. The availability of such models allows us to test and assess the viability and feasibility of simulation protocols and algorithms. The basic approach employed in this study is to take real movement data and construct a parametric model that can be used to generate synthesized movement data that closely follow the original, real data (in terms of their statistical properties). To accomplish this, the project worked with the movement data traces collected over the Dartmouth campus. Specifically these are timed user registration data between individual computers and the wireless LAN base stations. The main challenge of this work was to reconstruct user movement (fine-grained) from the coarse-grained trace data. The project employed a detailed analysis of the data available from the base station registrations. It then combined that data with a detailed building and road map of the Dartmouth campus, and incorporating a number of human movement heuristics studied by sociologists. This project also obtained access to movement data from military exercises. Future project work will apply similar methodologies to the exercise data traces.
- A simulation module of the ZigBee (IEEE 802.15.4 standard) [ZigBee] medium access control architecture for the NS2 simulator was developed. This module enabled the team to properly evaluate the mobility models developed. It also afforded the opportunity to study a number of applications using developed mobility models. This study allows the research team to accurately model and simulate a variety of application scenarios using the ZigBee PHY/MAC technique in conjunction with other layers currently provided by NS2. This module will also allow the generation of mobility data based on pre-specified rules

or policies. The completed module is expected to work with other NS2 components seamlessly. This new standard is going to gain increasing momentum and areas of application in the future. This work will also be of great value to the networking research community in general. This project completed the basic design and initial implementation of ZigBee (IEEE 802.15.4) simulation module.

The above outlines the main objectives, motivation and basic methodologies used in this project. In the next subsection we describe in more detail the research conducted under this project.

### 3.2 Research Conducted

Technical approaches used in this project include stochastic modeling and analysis (in analyzing mobility models and constructing/synthesizing mobility models from real trace data) and computer simulation (for developing the ZigBee MAC simulation module). The innovative aspect of the approach lies in the combination of these techniques. The research started with the measured movement data to stochastic modeling of mobility, and then to simulation study of mobile systems. This combination is unique, and proved to be effective in achieving the project's objectives outlined earlier. This subsection will describe the work conducted during the project.

In analyzing and constructing stationary mobility models the team started by classifying random mobility models. Such models are typically characterized by a collection of nodes placed within a confined space  $U$ , which move according to certain underlying random processes. Each node selects two or more of the following, according to some random distributions: a destination  $d$  in  $U$ , a traveling speed  $v$ , an angle  $a$ , and a travel time  $t$ . It then travels to  $d$  at  $v$ , or travels at  $v$  along  $a$  for  $t$ , and so on. After reaching  $d$  or having traveled for  $t$ , the node may pause before repeating the process. The precise means of selecting  $U$ ,  $d$ ,  $v$ ,  $a$ , and  $t$  differ from model to model. In [Camp02] these models are categorized into *entity* mobility models, where individual nodes move independently of each other, and *group* mobility models, where the movement of a group of nodes may be correlated [Hong99]. The research team studied both models and subsequent discussions will refer to both models as *random mobility model*.

As the behavior of most mobile systems depends heavily on the movement of constituent nodes, it is highly desirable to have a mobility model that generates stable nodal movement. The mobile system needs to maintain a steady level of mobility over time, e.g., a fixed average nodal speed and a fixed speed variance. This is especially critical for simulation studies that present performance metrics as time averages. The research team's recent work [Yoon03Infocom] shows that one of the most widely used, the *random waypoint* model, has a transient period in which the average nodal speed decreases to a steady-state level (below the initial average) as the simulation goes on. Such speed decay can have a dramatic influence on measured performance and overhead. Consequently, time-averaged metrics during this period of decay can not be presented as the underlying process if not stationary.

There are a number of ways to mitigate the negative effect of this transient speed decay. For example, narrowing the range from which to select speeds can reduce the degree of decay and the time required to reach a steady state. However, it limits the speed variation and does not remove decay in principle. Another approach is to *warm-up* every simulation by running it until reaching the steady state and then discarding the initial data. While this is valid, it is cumbersome, because the duration of this settling period is generally case-dependent, making the simulation process prone to error.

The objective of this study was to develop *stationary* mobility models, i.e., those that do not have such transient speed decay, so that reliable time-averaged simulation produce reliable results without having to discard initial data. This project used a general derivation of the steady-state average speed distribution for several classes of random mobility models. The process showed that speed decay is not a property exclusive to the random waypoint model, but a rather common phenomenon. Any random mobility model that chooses speed and destination independently exhibits a similar transient period in which the speed decays. The intuition is that nodes travel for longer times at lower speeds if the destination is chosen independently of the nodal speed. This result is true *independent* of the specific distribution from which speeds are chosen, or the mechanism with which destinations are determined. Furthermore, if pause time between successive trips is set to zero, the distribution governing the steady-state average speed is *independent* of the mechanisms used to determine destination; it depends only on the distribution from which speeds are chosen.



Based on the findings the study showed how this transient period and speed decay can be completely eliminated. Speed decay is eliminated by constructing a composite random mobility model from any random mobility model that exhibits speed decay. The key is to initialize the simulation in the steady state by selecting the speed of the first trip from the steady-state speed distribution, and selecting speeds of subsequent trips from the original speed distribution. This method is orthogonal to any modification to a random mobility model for obtaining desired spatial distribution of nodes, e.g., uniform distribution within the movement area. System warm-up may still be needed if the simulated mobile system starts from a “cold state”. However, by having such stationary mobility models, warm-up is no longer needed for nodal movement, freeing the experimenter to consider other matters.

The fact that current mobility models are not sufficient for realistic study of mobile ad hoc systems was the motivating factor for the second component of this project. The study adopted a stochastic approach to extract mobility models from real movement data. Under this project, the team obtained the mobility data traces collected by colleagues at Dartmouth College over the past two years. These are movement traces collected via wide deployment of IEEE 802.11 base stations over the Dartmouth campus. The idea was to map the data traces into routes taken by users. The key to the project’s approach was to find shortest (major) routes of all AP (access point) pairs and get the probability distribution of which road were taken at the (major) intersections. The team could then extract all the AP changes of each MAC address and build a probability transition matrix by counting the decisions at each intersection. Since a previous road taken affects the probability of next road taken, 2nd or 3rd order Markov chain were also considered. Processed data created a transition probability matrix. The matrix was built on the 118 AP locations on campus along with major intersections and buildings. Certain assumptions were made concerning the routing behavior of humans. We borrowed findings from sociological studies to confirm or revise these assumptions.

Regarding the third component of this project, the coding part of the proposed implementation of a ZigBee (IEEE 802.15.4) simulation module for the NS-2 simulator was completed. This module consists of two stages, CAP (contention access period) and CFP (contention free period). The first stage is modeled/coded after the existing NS-2 code for 802.11, while the second stage is modeled/coded after the existing NS-2 code for TDMA. Extra timers and mechanisms to coordinate the two staged are also implemented. The team added the ZigBee-specific packet types and definitions; the version of CSMA to be used within the CAP stage; and the version of the TDMA to be used within the CFP stage. The first phase of debugging and testing of the MAC layer was planned but not completed under this project.

## 4 RESULTS AND DISCUSSION

### 4.1 Summary of Results

We obtained three pieces of results/software:

- (1) A general framework with which stationary mobility models may be constructed. This includes the modified random waypoint model, which has already been released with the most recent version of NS2 simulator.
- (2) Synthetic mobility models in the form of a combination of the terrain map (in this case the Dartmouth campus map) and probability transitions describing user movements, based on real movement data.
- (3) The simulation module of IEEE 802.14.5, as an independent utility within the NS2 simulator framework. This module will be given to University of Southern California's ISI (Information Science Institute) where NS2 is maintained and updated.

In addition to the above, the team delivered and disseminated research results from this project via conference and journal papers. Journal paper [Yoon05TMC] is going to appear in IEEE Transactions on Mobile Computing in 2005. This is a summary of the project's work on the analysis and construction of stationary mobility models for mobile ad hoc network simulation studies. This paper extends previous framework established in [Yoon03Infocom] and [Yoon03Mobicom] in that it studied various group mobility models where nodes' movement is correlated. It also addressed the relative speed decay problem that is often used in the literature in addition to the average node speed. Through this sequence of research papers, our team was the first to identify the serious flaw with the widely used random waypoint mobility model within the ad hoc networking community, and the first to come up with a sound solution with which stationary mobility models may be constructed. This work has had major impact on the research community as mobility models are indispensable in the simulation studies of ad hoc networks. The team is currently working on a report on the construction of mobility model based on real trace data.

### 4.2 Discussion and Impact of Results

The research work on identifying the problems with existing mobility models and the way they are used in ad hoc network simulations has already had significant impact on the research community. In particular papers [Yoon03Infocom] and [Yoon03Mobicom] are very widely cited by peer researchers, *with [Yoon03Infocom] listed as the fourth most cited paper published in 2003 by citeseer.*

University of Michigan's work on building good realistic mobility model will also have a great impact on the ad hoc networking research community, as we are currently lacking mobility models capable of producing realistic movement. This work will make the studies on mobile systems much more applicable.

The ZigBee simulation module will allow researchers to accurately model and simulate a variety of application scenarios seamlessly along with other layers currently provided by NS2. This work will also be of great value to the networking research community, as the ZigBee standard becomes more widely used. One example application is service assistance in an indoor pervasive computing environment. In this environment, small ZigBee devices are deployed in a large office building as distributed data storage, from which visitors can obtain useful information. Good mobility models can serve prediction purposes and help enhance the efficiency of the system and improve user perceived quality of service. With the ZigBee simulation, module researchers can effectively study a number of design choices on network architecture and fine grained link scheduling. This study gave the research team good experience and guidelines in designing such systems.

## 5 CONCLUDING REMARKS

In this project, the research team performed studies on building sound mobility models for the simulation studies of mobile ad hoc networks. Specifically, this project aimed at developing tools and modules to better facilitate the study of mobile ad hoc networks, which tends to be heavily simulation based. The project approached this objective in three aspects: (1) to develop mobility models that are stationary and mathematically tractable, (2) to develop mobility models that more closely represent real movement, and (3) to develop a simulation module with which mobile application scenarios can be better studied. Technically this project addressed the area of stochastic modeling, renewal theory and computer simulation. In particular, it involves building better mobility models that capture the characteristics of movement pattern in different scenarios, as well as simulation modules that enable applications utilizing such mobility models. Overall, this project has been very successful, with part of the results already transferred and disseminated to the research community.

## 6 RECOMMENDATIONS

University of Michigan is grateful to the DARPA Network Modeling and Simulation (NMS) program for funding this project. The support was essential for the results obtained and reported in this document. The support was also critical in the training of a graduate student in the process of completing his PhD degree. There remain many open problems and challenges in the modeling and simulation of mobility in ad hoc networks, and more broadly modeling and simulation issues in all types of networks. The research team believes that continued funding in similar areas will be instrumental in the advances and developments in these areas, and can potentially make significant impact in the design, practice and operation of next generation networks.

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